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External Air Pollution Costs of Telework*

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Abstract

Background, Aims and Scope. Telework is associated with a number of costs and benefits, including reduced company overhead costs, need for office and parking space, office energy consumption, increased productivity, reduced absenteeism, retention of specialized employees, reduction in transportation-related fuel consumption and air pollution, and many others. This paper applies a systems model to telework and nontelework scenarios to quantify direct energy and fuel costs and external costs related to air emissions from transportation, heating, cooling, lighting, and electronic and electrical equipment use both at the company and the home office, including rebound effects.

Methods. E-COMMUTair, a scalable web-based tool created by the authors and designed to assess the air pollution effects of individual or company telework programs versus nontelework is employed along with Monte Carlo simulation and sensitivity analysis. E-COMMUTair is using the latest available U.S. energy use and air emission factors. The external costs of air emissions are estimated. The role of telecommuting frequency is emphasized, and differences between various states are explored. The paper identifies the drivers of external costs, and presents an example breakeven analysis focused on CO_2 and key model parameters.

Results and Discussion. Nontelework's external costs are equal to or higher than telework's costs for every model component, demonstrating that telework programs could provide benefits, including monetary benefits, to society. Transportation is the major contributor to the total costs, with home heating and cooling, and office cooling following. Most of the monetary costs associated with transportation are borne by individuals rather than society. Teleworking employees increase their home-related expenses but reduce their travel-related expenses, ending up with smaller total costs. Energy and fuel costs get reduced in the office space when telework programs are applied, resulting in benefits to companies. Energy and external costs decrease as telework frequency increases. When compared to not teleworking, 5-day telework scenarios on cooling days in California can have about 50–70% lower total costs. The probabilistic analysis confirms the results of the deterministic analysis. The sensitivity analysis reveals that for the nontelework scenario, transportation-related variables such as commuting distance and average number of passengers affect CO_2, CO, and NO_x emissions, while for the telework part, frequency and the number of roundtrips are the most relevant.

Conclusions. Both analyses show that telework programs have the potential to lower both energy and external costs creating a favorable bottom line for society, employees, and companies by decreasing tailpipe emissions, lowering transportation costs, and decreasing energy costs at the company office. However, important parameters such as telecommuting frequency, characteristics of the office and home space, climate patterns, and rebound effects that determine external costs along with the price of gasoline, electricity and natural gas in the state where the program is implemented can greatly influence the final results, and should be carefully examined.

Recommendations and Perspectives. The effects of telework programs on people's daily lives are complex and difficult to predict and quantify. The current analysis showed that significant financial benefits can be expected from telework programs, but as seen often in environmental policy-making, the details of implementation will make or break the success of a program.

Keywords: Air emissions; energy; external costs; Monte Carlo simulation; sensitivity analysis; telecommuting; telework

Introduction

Telecommuting and telework (TW) are terms often used interchangeably. In this paper, telework is defined as the use of telecommunications and information technology for work purposes, including home-based workers who may never have to commute to a central company office, as well as company employees who are working away from the company office at least one day a week.

Over the years, telework programs have become associated with a number of benefits, including economic savings to companies attributed to such factors as reduced overhead costs, need for offices and parking spaces, office energy consumption, increased productivity and reduced absenteeism, retention of specialized employees, avoidance of employee relocation, minimization of security and other risks, time savings, as well as reduction in gasoline consumption and air pollution [1–5]. Costs identified in literature such as increased energy usage at home, remote access, equipment and program set up costs do not seem to overcast the general expectation that telework could increase profits. Utility costs in individuals' homes could increase, but commuting and vehicle maintenance costs and other daily expenses (e.g., dry cleaning) could decrease, ensuring a favorable bottom line [3].

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When adopted with attention to economic and environmental criteria, telework can have a positive overall impact on the economic bottom line, and can prove to be a profitable relationship for all parties involved, i.e., organizations, individuals, and society. Numbers for quantified savings are scanty, partly due to the lack of a universally applicable definition of telework (e.g., how many days a week does one telework?) and the variety in the scope of telework programs. However, numbers are emerging. Matthews and Williams [6] analyzed telework's macrolevel effects on energy use in three sectors, transportation, commercial, and residential buildings, and found that for current estimates of telework practices in the United States and Japan, national level energy savings would be only 0.01–0.4% in the United States and 0.03–0.36% in Japan. If telework would become more widespread in the future, where, e.g., 50% of information workers would telework four days per week, the U.S.' and Japan's energy savings would be about 1%, which is modest relative to currently available policy options to reduce energy demand. For example, an average vehicle fuel use reduction of 20% would save 5.4% of total U.S. energy demand. In examining potential economic benefits, AT&T had announced that it expected up to $150 million in telework-related benefits in 2003 [7]. AT&T has reportedly saved $550 million in real estate since 1991 (approximately $3,000 per office) [3]. IBM had a similar experience saving $700 million in real estate costs by having almost 25% of its employees telecommute [3]. Other estimates of such savings range from $1,500 to $6,000 per person per year or up to 30 or 40% of currently leased space [5]. Another study estimated that if the average home teleworker shared company office space with only one other person, it would result in direct reduction of 1.6 million offices nationwide, resulting in millions of dollars of savings [8]. A state study conducted in North Carolina in 1997 estimated net savings of $23 million for 5% of the workforce teleworking [3].

Although productivity increases and the related benefits are hard to quantify, most studies agree that telework is responsible for productivity increases of 10–20% on average, up to 40% [5]. Despite sporadic evidence to the contrary, companies such as AT&T, Compaq, IBM, and American Express report productivity increases of 15–50% [3,8]. AT&T has estimated that those increases have earned the company $100 million [7], while other studies estimate that savings for any given company with telework programs in place are at least $5,000 per employee per year [3].

Retention of employees is one of telework's major advantages which can be associated with significant cost savings considering that training a new employee costs $20,000–25,000 [5]. Pacific Bell has estimated these costs to be as much as $100,000 [5]. AT&T's estimated total savings are $15 million [7]. Retention of employees over longer periods of time can also lead to productivity improvements of 15–30%, which a survey estimated to bring average annual benefits of $10,000 per teleworker [8].

Relocation expenses for employees (due to corporate changes such as mergers and reorganization) can be significant especially when employees own a house. Telework helps employees avoid such costs and maintain their residence independent of where their company office is located, helping them to save between $10,000 and $50,000 [5]. Absenteeism and related expenses can also be reduced due to telework. When employees are working at home, they possibly do some work even in case of illness as long as they do not need to leave the house. Reduction of absenteeism and sick leave when working at home has been estimated at 20–25% [3,5,9] which reduces replacement costs (employee substitution) and contributes to higher overall productivity.

1 Research Goals

A number of telework cost-benefit analyses have been conducted assuming either a macro-scale approach focused on the public and private sectors, or a micro-scale approach focused mostly on individuals [1,10–14]. These reports accounted for costs and benefits related to, among others, office equipment, office operating costs, parking, employee productivity, and travel-time savings. The principal assumptions and conclusions of some of the most important among these reports, along with their strengths and weaknesses, were summarized and served as the basis for the most comprehensive telework cost-benefit analysis to date [1]. This analysis attempted to combine the knowledge acquired from those previous efforts with new information, economic and statistical theory to estimate public, private and individual costs. The deterministic portion of the analysis suggested that individuals are the primary beneficiaries of telecommuting, while the respective stochastic part suggested that benefits to companies, though uncertain, can be large when conditions are favorable [1].

The current paper does not attempt to perform a cost-benefit analysis, but rather it explores the external environmental costs and benefits associated with telework by performing both deterministic and probabilistic analyses. External costs are real costs not incurred by the producer but by society. For example, such costs are related to the effects on humans of tailpipe or electricity generation emissions. Estimating external costs is very useful since it helps account for the social and environmental aspects of any project or program by offering a commonly appreciated metric (dollars). They also serve as indicators of areas in need of better pollution prevention and control measures [15].

Previous reports focused solely on the monetary costs of transportation-related air pollution impacts of telework. In addition to those costs, this analysis quantifies the external monetary values associated with the air pollution impacts of the other components of a telework system: energy consumption in the company office and the employee's home, including rebound effects due to heating, cooling, lighting, and the use of electronic and electrical equipment. The results are examined based on the 'public-private-individual' approach. These costs were not monetized in any of the previous studies. Estimates of direct fuel and energy costs are estimated and contrasted to the respective external costs. The role of telecommuting frequency is emphasized, and differences between various states are explored. This paper also identifies the parameters of the analysis that are driving external costs, and focuses on CO_2 to provide an example of important model parameters that ensure that the respective

telework-related emissions and the associated costs do not exceed nontelework (NTW) ones. The goal of this paper is to bring attention to the environmental aspects of telework programs by utilizing deterministic and probabilistic methods and environmental valuation.

2 Telework Model

Both the deterministic and the probabilistic analyses are performed using E-COMMUTair, a scalable web-based tool designed to assess the air pollution effects of individual or company telework programs versus nontelework using the latest available U.S. energy use and air emission factors [16,17]. The model accounts comprehensively for the most important environmental effects (EI) and costs (except land use): transportation (TR), electronic and electrical equipment use (EE), and heating, cooling and lighting in the home office (HS) and in the company office (OS):

$$EI_{NTW\ or\ TW} = EI_{TR} + EI_{EE} + EI_{HS} + EI_{OS} \quad (1)$$

Air pollutants have serious public health impacts that need to be accounted for. Our model in its current version quantifies emissions of greenhouse gases, ozone precursors, and some criteria and hazardous air pollutants (CO_2, CO, NO_x, N_2O, PM_{10}, CH_4, SO_2, Hg). We have plans to extend the coverage to other air emissions as data become available. The external costs are currently estimated for CO_2, CO, NO_x, N_2O, CH_4, SO_2, and PM_{10} due to data availability.

2.1 Environmental costs

To estimate external costs, average monetary values of emissions are used (**Table 1**). The monetary values (in $/ton of pollutant emitted) are an average of a range of values based on existing literature, and are estimated using both the damage value method and the cost control method (see Table 1) [15,18]. The damage value method estimates air pollution damage values by simulating air quality, identifying health and welfare impacts of air pollution, and valuing the identified impacts. The cost control method estimates the marginal emission control cost. This represents the opportunity cost that could be offset by avoiding the need for spending on emission reductions from the most costly emission control measures available [19]. State Public Utilities Commissions in the U.S. have also suggested ways to cost the full impacts of electricity generation.

The differences observed in Table 1 between the minimum and maximum monetary values for each pollutant are mostly due to the lack of a uniform specification of the damage functions (which are complicated to determine, e.g., they are dependent on the proximity of population to air emission sources), differences in the scientific basis of air pollution modeling, and differences in the health effects included in the studies. Nonetheless, these values are a result of public policy processes, and satisfactorily represent the current situation.

In order to include the estimated emission values in the model, the costs were adjusted to 2002, the year of the environmental data (see Table 1), using the chain-weighted gross domestic product (GDP) price index.

2.2 Chain-weighted gross domestic product deflator

The chain-weighted GDP price index is a measure of inflation that tries to estimate how much it would cost to buy the same basket of goods today as in the previous year. It was adopted by the U.S. Department of Commerce's Bureau of Economic Analysis in 1995 [20]. The chain-weighted index seems preferable over fixed-weighted indices since the latter tend to distort growth by not taking into account the fact that relative prices change over time. For example, the relative price of computers today is lower compared to 10 years ago. Thus, using a fixed-weighted index would overvalue the price of computers today. On the other hand, indices such as the GDP deflator do not consider new goods introduced to the market, e.g., cell phones, and tend to underestimate actual val-

Table 1: Emission valuation: $/ton of pollutant emitted (1992$) [15] and $/ton of pollutant emitted (inflated by chain-weighted GDP index to 2002$)

		$/ton of pollutant emitted (1992$)			
Pollutant	**studies (no.)**	**min**	**median**	**mean**	**max**
carbon monoxide (CO)	2	1	520	520	1,050
nitrogen oxides (NO_x)	9	220	1,060	2,800	9,500
sulfur dioxide (SO_2)	10	770	1,800	2,000	4,700
particulate matter < 10 microns (PM_{10})	12	950	2,800	4,300	16,200
volatile organic compounds (VOC)	5	160	1,400	1,600	4,400
global warming potential (in CO_2 equivalents)	4	2	14	13	23
		$/ton of pollutant emitted (inflated by chain-weighted GDP index to 2002$)			
carbon monoxide (CO)	2	1.2	620	620	1,260
nitrogen oxides (NOx)	9	270	1,270	3,350	11,360
sulfur dioxide (SO_2)	10	920	2,150	2,390	5,620
particulate matter < 10 microns (PM_{10})	12	1,140	3,350	5,140	19,360
volatile organic compounds (VOC)	5	190	1,680	1,910	5,260
global warming potential (in CO_2 equivalents)	4	2	17	16	27

ues [21,22]. The chain-weighted GDP index was selected over the Consumer Price Index (CPI) because the CPI focuses only on goods and services that households pay for directly, thus is inappropriate for valuing emissions.

3 Basis of Telework Scenarios

The telework scenarios used to conduct the analyses in this paper are based on U.S. emissions data and national average values for typical U.S. teleworkers obtained mainly from the literature and surveys [23–30]. The scope and assumptions in these studies are different, and this represents an ongoing problem in telework research. We acknowledge that commuting and work patterns may be different in other countries, and there may be differences worldwide in commute mode and distance, rebound effects, efficiency of heating and cooling of company and home offices, emission factors from energy use and electricity generation, and other factors. The energy use in the model relied on published data about the end use of energy of electrical and electronic equipment, and heating, cooling, and lighting systems, and tailpipe emissions of a passenger car. The rest of life-cycle energy use numbers (e.g., from manufacturing) were not included. The telework scenarios presented herein, along with the underlying assumptions, were first presented and explored in detail by the authors in publication [17], which aimed to quantify greenhouse gas and other telework-related air emissions. A summary of these assumptions is presented below. For a typical case reflecting U.S. telework patterns, the analysis found that telework has the potential to reduce air emissions although it may not affect equally the emissions of all types of pollutants. Scenarios can be constructed when telework is not the environmentally preferable choice over nontelework. Environmentally beneficial telework programs were found to depend mainly on commuting patterns, characteristics of the office and home space, equipment use, and rebound effects. Rebound effects included in both publication [17] and the current analysis are induced (or nonwork-related) travel, induced equipment use, and induced energy use.

Induced travel is for leisure, social, and other purposes that would not have occurred if it were not for employee telecommuting and for a possibility to avoid the daily commute to work. Induced equipment use refers to the additional use of equipment such as kitchen appliances and the TV when an employee chooses to work from home. Induced energy use is the resulting additional use of lighting, heating or cooling equipment due to an employee spending more hours at home than in a nontelework scenario. This analysis explores how telework costs differ both when rebound effects are accounted for and when they are not. The effects of telework frequency are also addressed as the impacts of a nonteleworking employee are compared with those of the same employee teleworking 1, 3, or 5 days per week. The assumption for the 3- and 5-day telework cases is that the company office is shared with a co-worker. As each state has a different electricity mix and a different climate affecting heating and cooling usage, the deterministic analysis is also used to estimate how the geographic location of a teleworking employee impacts the final results.

The basic underlying assumptions for the telework scenarios (more thoroughly presented in publication [17]) are:

→Transportation

Mode of transportation:
- Honda Accord, a typical midsize sedan in the United States with average 'environmental friendliness' rating [23]

Average occupancy [24]**:**
- 1 person for commute trips
- 2 persons for noncommute trips

Commute distance:
- 12 miles (one-way) [24]

Induced distance traveled:
- 6 miles (assumed based on a number of surveys reported in [24,25])

→Electronic and Electrical Equipment Use

Company office:
- Copiers, printers, and fax machines are shared with co-workers
- Desktop computer, phone: individual use

Home office:
- Use of desktop and laser printer [26]
- Induced usage of appliances such as TV, stereo system, gas range and oven, dishwasher, washing machine, and dryer

→Heating, Cooling, and Lighting

Company and home office [26]**:**
- Natural gas air furnace for heating
- Central air conditioning for cooling

Home office [26]**:**
- Incandescent bulbs

Company office:
- Lighting usage is estimated based on floor area, and is assumed to be centrally controlled.

4 Deterministic Analysis

A deterministic analysis was conducted to quantify fuel, energy and external costs for 1,000 nonteleworking employees versus the same costs for 1,000 1-day, 3-day and 5-day teleworkers. The assumed location for these scenarios is California. The basic assumption for the nontelework portion of the scenario is that when one is not teleworking, one only does very little supplementary work at home which is not considered to have any impact on the usage of heating or cooling equipment and lighting, but which does result in some additional use of the existing home electronic equipment such as a computer or a printer [17,26,27]. For the telework portion, the assumption is that the employee is working 1, 3 or 5 days per week. As telecommuting frequency increases, telework is assumed to increasingly affect employees' daily habits resulting in induced usage of electronic and electrical equipment at home.

Table 2 presents the external environmental costs and the energy and fuel costs as calculated for these three telework scenarios. The energy and fuel costs are calculated based on the assumed consumption patterns for the different scenarios. The external costs are calculated by multiplying the resulting emissions from these scenarios by their costs presented in Table 1. The same scenarios are then applied to other states to examine how geographical differences in terms of heating and cooling usage, electricity mix, pricing and taxation affect the final results [26,28,31,32].

Table 2: Results of deterministic analysis (*reported to two significant digits)

		External Costs ($)			Energy & Fuel Costs ($)	Total Costs ($)*		
		min	mean	max		min	mean	max
Transportation	NTW	152	2,398	5,463	7,785	7,900	10,000	13,000
	1-day TW	125	1,968	4,472	6,421	6,500	8,400	11,000
	3-day TW	72	1,125	2,551	3,637	3,700	4,800	6,200
	5-day TW	17	258	586	852	870	1,100	1,400
	No rebound (5-day TW)	0	0	0	0	0	0	0
Office Electronic	NTW	5	36	71	1,104	1,100	1,100	1,200
and Electrical	1-day TW	5	32	63	981	990	1,000	1,000
Equipment	3-day TW	3	22	43	675	680	700	720
	5-day TW	0	0	0	0	0	0	0
	No rebound (5-day TW)	0	0	0	0	0	0	0
Home Electronic	NTW	1	6	12	174	180	180	190
and Electrical	1-day TW	5	37	73	603	600	640	680
Equipment	3-day TW	18	145	288	2,429	2,400	2,600	2,700
	5-day TW	28	222	442	3,803	3,800	4,000	4,200
	No rebound (5-day TW)	5	32	63	900	900	930	960
Office Lighting	NTW	5	37	72	1,104	1,100	1,100	1,200
	1-day TW	5	37	72	1,104	1,100	1,100	1,200
	3-day TW	2	18	35	540	540	560	580
	5-day TW	0	0	0	0	0	0	0
	No rebound (5-day TW)	0	0	0	0	0	0	0
Home Lighting	NTW	0	1	2	28	28	29	30
	1-day TW	0	3	7	101	100	110	110
	3-day TW	2	11	22	309	310	320	330
	5-day TW	3	18	36	512	520	530	550
	No rebound (5-day TW)	1	10	19	264	270	270	290
Office Heating	NTW	7	59	118	509	520	570	630
	1-day TW	7	59	118	509	520	570	630
	3-day TW	3	28	55	238	240	270	290
	5-day TW	0	0	0	0	0	0	0
	No rebound (5-day TW)	0	0	0	0	0	0	0
Office Cooling	NTW	28	199	390	6,012	6,000	6,200	6,400
	1-day TW	28	199	390	6,012	6,000	6,200	6,400
	3-day TW	13	93	183	2,822	2,800	2,900	3,000
	5-day TW	0	0	0	0	0	0	0
	No rebound (5-day TW)	0	0	0	0	0	0	0
Home Heating	NTW	0	0	0	0	0	0	0
	1-day TW	12	105	209	1,006	1,000	1,100	1,200
	3-day TW	37	317	632	3,036	3,100	3,400	3,700
	5-day TW	63	533	1,063	5,124	5,200	5,700	6,200
	No rebound (5-day TW)	63	533	1,063	5,124	5,200	5,700	6,200
Home Cooling	NTW	0	0	0	0	0	0	0
	1-day TW	5	32	63	900	910	930	960
	3-day TW	14	97	190	2,701	2,700	2,800	2,900
	5-day TW	23	162	317	4,502	4,500	4,700	4,800
	No rebound (5-day TW)	23	162	317	4,502	4,500	4,700	4,800
Total for Heating Days	*NTW*	172	2,550	5,782	10,705	11,000	13,000	16,000
	1-day TW	159	2,239	5,002	10,726	11,000	13,000	16,000
	3-day TW	138	1,658	3,609	10,864	11,000	13,000	14,000
	5-day TW	111	1,029	2,122	10,291	10,000	11,000	12,000
	No rebound (5-day TW)	69	577	1,153	6,289	6,400	6,900	7,400
Total for Cooling Days	*NTW*	192	2,678	6,008	16,208	16,000	19,000	22,000
	1-day TW	171	2,300	5,107	16,123	16,000	18,000	21,000
	3-day TW	124	1,508	3,304	13,112	13,000	15,000	16,000
	5-day TW	70	655	1,367	9,669	9,700	10,000	11,000
	No rebound (5-day TW)	28	203	397	5,666	5,700	5,900	6,100

4.1 Discussion of results

Table 2 reveals that transportation is the major contributor to the total costs associated with the nontelework as well as the three telework scenarios, with home heating and cooling, and office cooling following. For the transportation component, the fuel costs are approximately three times higher than the mean external costs, signifying that most of the monetary costs associated with transportation are borne by the individuals rather than by society. Energy and fuel costs are higher than the external costs of the rest of the model components, but external costs are significant in absolute terms for heating and cooling.

Nontelework's external costs are equal to or higher than telework's costs for every component, demonstrating that telework programs could provide monetary benefits to society. Energy and fuel costs get reduced in the office space when telework programs are applied, but increase when accounting for the home space reflecting the shift of both emissions and expenses to a different source. Overall, resulting home expenses assumed by a teleworking individual are higher compared to the ones incurred by the company were the employee to keep working in the company office. One could argue that companies are reducing their expenses while the employee's costs rise; however, when accounting for the decrease in transportation-related costs, favorable economics can be observed for the employee as well.

As telework frequency increases, both energy costs and external costs decrease. The most significant reductions are observed in the two 5-day scenarios (with and without rebound effects) on cooling days. When compared to not teleworking, the two 5-day telework scenarios have about 50% and 70% lower total costs, respectively. In Table 2, the observed maximum decrease in the mean external costs as well as energy and fuel costs for individual model components is about tenfold, or even total elimination for some components of the 5-day telework scenario or when rebound effects are eliminated, with the absolute differences being higher in the case of energy and fuel costs indicating how important it is to control this type of cost.

4.2 Cost differences by state

The above results are based on emissions associated with teleworking employees located in California. In this part of the analysis, the results are compared to estimates for employees located in major telecommuting states or in states with the highest or lowest CO_2, SO_2 or NO_x emissions from electricity generation [17,32]. Idaho had the lowest and North Dakota the highest CO_2 and NO_x, while Rhode Island the lowest and Ohio the highest SO_2 emission factors. The values used to calculate the external costs are the same for all states, however, the prices of gasoline, electricity and natural gas presented in **Table 3** differ [28,31]. These prices are based on state averages for 2002, and reflect differences in taxation and value of particular goods [28,31]. Electricity and natural gas prices differ not only between the states, but also between the sectors. The values used to calculate home-related costs are those reflecting the residential sector, while for the calculation of the office-related costs, the values used were the averages for the commercial sector.

For the states examined, the mean external costs are consistently lower for telework, while energy and fuel costs vary (**Table 4**). The energy and fuel costs of not teleworking are higher than for teleworking in the cooling season, but comparable or lower in the heating season. Total costs are consistently lower for the 3-day telework scenario than for the nontelework scenario in the cooling season, but comparable or lower for nontelework in the heating season.

5 Probabilistic Analysis

A probabilistic analysis was conducted to assess the underlying uncertainty in the data that can affect the results of the deterministic analysis. The probabilistic analysis was based on the same core 3-day scenario used in the deterministic analysis, but no differentiation was made between the heating and cooling season, and the use of miscellaneous equipment at home when someone is teleworking was more dominant [17]. The goal was to explore how telework-related costs change when a certain amount of uncertainty is incorporated into the analysis. The probabilistic analysis reveals

Table 3: Electricity, natural gas and gasoline prices for the residential and commercial sectors for different states [10,11]

	Electricity (cents/kWh)		Natural gas ($/thousand cubic feet)		Gasoline (cents/gallon)		
State	**Commercial**	**Residential**	**Commercial**	**Residential**	**Fuel price**	**Added Tax**	**Total**
California	12.2	13.3	9.33	10.43	98.2	50.4	148.6
Georgia	7.7	6.5	9.19	10.58	86	30.6	116.6
Idaho	6.8	5.8	7.58	8.48	93	43.4	136.4
Illinois	8.4	8.3	8.55	9.04	96.4	48.4	144.8
New York	13.5	12.1	9.61	11.75	91	48.7	139.7
North Dakota	6.5	6	6.96	7.68	99	39.4	138.4
Ohio	8.1	7.7	8.67	9.67	92.2	40.4	132.6
Rhode Island	10.2	8.4	10.69	12.17	91.4	49.4	140.8
Texas	8.1	6.8	6.49	8.9	86	38.4	124.4

Table 4: State differences in external, fuel, and energy costs of nontelework and telework scenarios (*reported to two significant digits)

	External Costs ($)			Energy & Fuel Costs ($)	Total Costs ($)*		
	min	mean	max		min	mean	max
Heating Season							
	Nontelework scenario						
California	174	2,580	5,836	10,705	11,000	13,000	17,000
Georgia	292	2,989	6,787	8,190	8,500	11,000	15,000
Idaho	143	2,194	4,946	6,865	7,000	9,100	12,000
Illinois	312	3,118	7,095	10,209	11,000	13,000	17,000
New York	190	2,252	5,068	7,507	7,700	9,800	13,000
North Dakota	336	3,178	7,222	10,694	11,000	14,000	18,000
Ohio	362	2,961	6,832	8,717	9,100	12,000	16,000
Rhode Island	163	2,371	5,302	8,333	8,500	11,000	14,000
Texas	234	2,940	6,626	9,082	9,300	12,000	16,000
	Telework (3-day scenario)						
California	137	1,657	3,599	10,864	11,000	13,000	14,000
Georgia	294	2,258	5,023	8,576	8,900	11,000	14,000
Idaho	144	1,675	3,596	8,708	8,900	10,000	12,000
Illinois	338	2,592	5,730	11,591	12,000	14,000	17,000
New York	216	1,970	4,251	9,971	10,000	12,000	14,000
North Dakota	378	2,861	6,346	13,037	13,000	16,000	19,000
Ohio	427	2,803	6,291	11,506	12,000	14,000	18,000
Rhode Island	168	1,878	3,961	10,349	11,000	12,000	14,000
Texas	213	2,101	4,622	9,094	9,300	11,000	14,000
Cooling Season							
	Nontelework scenario						
California	194	2,708	6,063	16,208	16,000	19,000	22,000
Georgia	525	3,982	9,106	10,899	11,000	15,000	20,000
Idaho	137	2,147	4,869	6,494	6,600	8,600	11,000
Illinois	523	3,990	9,194	12,022	13,000	16,000	21,000
New York	265	2,598	5,854	8,641	8,900	11,000	14,000
North Dakota	610	4,499	10,329	14,764	15,000	19,000	25,000
Ohio	702	4,359	10,221	11,520	12,000	16,000	22,000
Rhode Island	181	2,515	5,544	9,502	9,700	12,000	15,000
Texas	359	3,647	8,216	11,988	12,000	16,000	20,000
	Telework (3-day scenario)						
California	125	1,513	3,320	13,112	13,000	15,000	16,000
Georgia	505	3,022	6,893	9,099	9,600	12,000	16,000
Idaho	77	1,115	2,496	3,836	3,900	5,000	6,300
Illinois	417	2,655	6,118	8,307	8,700	11,000	14,000
New York	202	1,645	3,655	6,188	6,400	7,800	9,800
North Dakota	504	3,231	7,398	11,292	12,000	15,000	19,000
Ohio	589	3,215	7,549	8,897	9,500	12,000	16,000
Rhode Island	118	1,452	3,099	6,591	6,700	8,000	9,700
Texas	306	2,522	5,605	9,827	10,000	12,000	15,000

the parameters that drive external costs by matching them with their respective emissions, and highlights the values of the parameters that help telework emissions to at least balance out nontelework ones.

5.1 Monte Carlo simulation and sensitivity analysis

Identifying which parameters have a determining effect on the final results of public or private programs is a key in directing resources and scientific research while ensuring a successful program outcome. Focusing on a few key elements could ultimately make a difference to a company's bottom line not only environmentally but also financially, and could help telework fulfill its role as a sustainable solution to air pollution problems. We created an MS Excel version of our telework model (E-COMMUTair Excel) to support Monte Carlo simulation and sensitivity analysis, and help users gain confidence in the interpretation of the model's outcome by identifying the driving parameters and exploring how the model reacts to the various inputs.

Monte Carlo simulation is a method used to model the inherent uncertainties of complex systems and to investigate the influence of crucial parameters. Modeling uncertainty is important for identifying the robustness of the final results. Simulation helps reproduce scenarios likely to occur in real life.

Monte Carlo simulation requires the user to determine the probability distribution of the different variables included in the model [33], and define how these variables interact by combining them in mathematical formulas. Defining the values and the distributions of the Monte Carlo variables can be a significant task as very often there are no supporting data in the literature. In this research, for most of the variables with mean values identified in the literature, the assumed distribution was normal, while in the case of somewhat or completely unknown variables, the distribution of choice was uniform, which assumes a known range and an equal likelihood of occurrence of all values. Another distribution used sporadically in the model is the triangular distribution which is helpful when there is a limited pool of data and which assumes a most likely value in the chosen range. The assumed standard deviation was based either on values from the existing literature, or when those were not available, it was set at 0.3 to better address the inherent uncertainty in the data set.

Although Monte Carlo simulation provides a range of possible outcomes for every parameter in question, it does not show which variables are critical for the output variation and have the greatest impact on the final outcomes. This is where sensitivity analysis can play a significant role. Crystal Ball was used to perform Monte Carlo simulation and sensitivity analysis [33]. Crystal Ball assumes that sensitivity is a combination of two factors, the forecast's sensitivity to the particular value of a variable, and the uncertainty associated with that particular value, and provides a sensitivity chart which indicates how much each variable affects the final result.

5.2 Results of probabilistic analysis

Table 5 shows that for a 3-day telework scenario both direct and external costs can vary significantly due to the uncertainty associated with the underlying data. Due to significant standard deviation of the mean values of the model components, it appears that telework-related costs could be higher than costs of not teleworking, suggesting that the correct implementation of telework programs is the key to success.

Table 5: Results of a 3-day probabilistic scenario per 1,000 teleworkers (*reported to two significant digits). TR = transportation; EE = electrical and electronic equipment; L = lighting; HC = heating or cooling

		Direct Costs ($)	External Costs ($)*	Total Costs ($)*
TW_{total}	***mean***	**3,278**	**1,100**	**4,400**
	st.dev	1,948	590	2,400
NTW_{total}	***mean***	**3,979**	**1,400**	**5,400**
	st.dev	1,938	770	2,600
TW_{TR}	***mean***	**1,937**	**730**	**2,700**
	st.dev	1,406	530	1,900
NTW_{TR}	***mean***	**2,882**	**1,100**	**3,900**
	st.dev	1,993	740	2,600
TW_{EE}	***mean***	**698**	**210**	**930**
	st.dev	1,352	170	1,500
NTW_{EE}	***mean***	**466**	**150**	**610**
	st.dev	165	73	200
TW_{L}	***mean***	**407**	**100**	**510**
	st.dev	141	54	170
NTW_{L}	***mean***	**399**	**140**	**540**
	st.dev	209	87	270
TW_{HC}	***mean***	**249**	**36**	**280**
	st.dev	88	18	99
NTW_{HC}	***mean***	**244**	**36**	**290**
	st.dev	106	18	120

Same as in the deterministic scenario, Table 5 indicates that the most significant contributor to telework's total costs is the transportation component which proves to be a significant financial burden on individuals but also on society through its high external costs. As Table 5 shows, the implementation of a telework program can help cut down these costs, benefiting both individuals and society. Nontelework- and telework-related costs are comparable for lighting, heating and cooling. A significant absolute difference is observed for the transportation component. For electronic equipment use, both direct and external costs are lower when one is not teleworking. This is expected since many pieces of office equipment are shared with other employees, hence the costs are also shared, while home equipment may be dedicated to work. Additionally, there might be a significant telework-induced usage of the electrical and electronic equipment at home. The probabilistic analysis confirms the results of the deterministic analysis that indicated that teleworking employees increase their home-related expenses but reduce significantly their travel-related expenses, ending up with a more beneficial overall outcome.

6 External Costs: Key Parameters

Table 6 presents the variables that affect most significantly the final outcomes for each of the pollutants in the model. For the nontelework part of the scenario, transportation-related variables such as commuting distance and average number of passengers appear to affect CO_2, CO, and NO_x emissions significantly, while for the telework part, frequency of telework and number of commute roundtrips are added to the list. These results underscore the fact that when an employee is teleworking, it is important to know how often that employee continues to commute to the office. Although not significant when exploring CO_2, CO, and NO_x, parameters related to home and company office energy consumption are important for other pollutants. Office size is a key parameter along with electricity and natural gas emissions indicating that nontelework-related values should be expected to vary by state as different states have different emissions rates for electricity generation. For the telework part, parameters related to rebound effects at home become important along with electricity emissions. The number of hours or the number of loads that miscellaneous home electrical or electronic equipment are used or not used when one is teleworking can prove critical to the final results. Transportation-related parameters do not affect this second set of pollutants as passenger vehicles in the model are only linked to CO_2, CO, and NO_x.

7 Breakeven Analysis

The scenario analysis tool was used to perform a breakeven analysis with respect to CO_2 emissions, selected because all components of the telework model contribute to CO_2 emissions no matter if the energy source is electricity or natural gas. The variables assumed for the scenario were the same as the ones used for the probabilistic analysis, except for the teleworking frequency which was assumed to be 1 day, 3 days and 5 days per week (**Table 7**).

Table 7: Results of breakeven analysis

	Default Values	1-day TW		3-day TW		5-day TW	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
NTW/TW CO_2		**1**	0.01	**1**	0.01	**1**	0.01
Office space size (ft^2)	**100**	**102**	28	**105**	28	**92**	28
Change in heating of home (%/7-day week)	**5**	**5**	1	**5**	1	**5**	1
% used for work purposes of NTW company PC (% personal active use)	**50**	**75**	15	**78**	14	**76**	13
% used for work purposes of TW company PC (% personal active use)	**0**	**10**	6	**9**	5	**10**	5
% used for work purposes of NTW home PC (% personal active use)	**0**	**25**	15	**26**	14	**26**	15
% used for work purposes of TW home PC (% personal active use)	**50**	**64**	9	**66**	8	**65**	8
No. of loads of electrical equipment use	**–1**	**0.4**	0.7	**0.3**	0.7	**0.4**	0.6
No. of hours of company office equipment use	**0**	**1.2**	0.8	**1.1**	0.8	**1.0**	0.8
Avg. no of passengers in vehicle	**1**	**3.0**	1.4	**3.0**	1.3	**2.8**	1.3
No. of commute roundtrips induced	**0**	**1.0**	0.6	**1.1**	0.6	**1.0**	0.6
No. of commute roundtrips in TW	**0**	**0.4**	0.3	**0.4**	0.3	**0.4**	0.2
Induced travel distance (miles)	**3**	**3.0**	1.9	**3.3**	2.0	**3.4**	2.2
Commuting distance (one way) (miles)	**12**	**12.3**	2.9	**11.6**	2.9	**11.5**	2.9

Table 6: Results of sensitivity analysis

Non-telework		Telework	
CO_2, CO, NO_x	N_2O, CH_4, PM_{10}, SO_2, Hg	CO_2, CO, NO_x	N_2O, CH_4, PM_{10}, SO_2, Hg
• commuting distance	• office space size	• average no. of passengers	• no. of hours of equipment use
• average no. of passengers	• electricity emissions	• telework frequency	• no. of loads of equipment use
	• natural gas emissions	• no. of roundtrips	• electricity emissions
		• commuting distance	

The goal of the breakeven analysis is to identify which combination of values of different variables would provide the breakeven point between CO_2 emissions incurred in a nontelework scenario versus a telework scenario. An indicative set of values for some of these variables for the three scenario analyses is presented in Table 7. When telecommuting frequency changes, Table 7 shows that the values of the different variables included in the model shift only moderately, but enough to ensure that nontelework and telework emissions break even. When deciding on a telecommuting program, a similar analysis or these values can serve as guidance for implementation and decision on the acceptable tradeoffs. Depending on how sensitive the final result is to a particular parameter, changing one value may or may not have a significant effect on the total results. If a specific parameter (such as commuting distance) is important, the adjustments required to the other components of the model in order to replace the lost equilibrium may be significant. The values presented in Table 7 should not be expected to ensure a breakeven NTW/TW ratio for all pollutants as the final result for each pollutant is determined by a different set of parameters.

8 Conclusions

The effects of telework programs on people's daily lives are complex, difficult to predict and quantify [34,35], and complicated by the rapid changes in access to telecommunications services and changes in the service industries in general [36–38]. The analysis presented in this paper focused on the environmental and economic aspects of telework programs. Based on a set of likely scenarios, we identified and quantified the key elements that should be considered when implementing a telework program, emphasizing the importance of parameters such as telework frequency, climate conditions, and state of residence (see Tables 2 and 4). The analysis aimed to quantify the external costs of telework, indicate the differences in the impact between external and direct energy and fuel costs (see Tables 2, 4, 5) (which should receive further LCA attention [39]), highlight some of the parameters that drive the environmental and financial success of telework programs (see Table 6), and show how the values of important telework parameters change when telework frequency changes (see Table 7). The analysis showed that significant financial benefits can be expected from telework programs, but as seen often in environmental policy-making, the details of implementation will make or break the success of a program.

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Life Cycle Assessment in the Telecommunication Industry: A Review

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Abstract

Background, Goal and Scope. Today, after the technologically and commercially successful breakthrough of electronic telecommunication facilities, rapid and globally untrammelled information exchange has become an indispensable service in daily life. Associated with the tremendous growth in electronic telecommunication hardware (GSMAssociation 2005), however, was and continues to be an increasing awareness of the environmental effects related to both the operation and the production, as well as the End-of-Life (EoL) treatment of such communication equipment. Environmental concerns, for example, have resulted in various governmental regulations such as the WEEE- (CEC 2003b) and the RoHS-directives (CEC 2003a).
To analyse, interpret and improve the environmental performance of electronic telecommunication equipment, life cycle assessment (LCA) is increasingly recognised as one promising analytical tool. Based on a thorough review of the scientific work and by discussing industrial views, this paper is intended to determine the key milestones achieved, to analyse the current research situation and to outline the key challenges concerning LCA and electronic telecommunication industries.

Method. Starting with a brief reflection of the LCA approach, the particularities in context with telecommunication products are discussed. Exemplary for various stakeholders participating in the supply chain of telecommunication means recent industry perspectives are also presented.

Results. In the core section of the proposed paper, the pertinent scientific literature on LCA and electronic telecommunication means is reviewed and the most impressive achievements are documented. Particular attention is dedicated to subcomponents of individual electronic telecommunication devices (e.g. Printed Wiring Board Assemblies (PWBA) of mobile phones), components of mobile communication networks (e.g. Base Transceiver Stations (BTS)) and entire networks concentrating on product comparisons, inventory approaches, impact assessment method development, result interpretations and presentation, and usability of LCA in decision-making.

Discussion. From the reviewed scientific literature and industry views, it was found that telecommunication products, in general, represent complex objects requiring a well thought-out performance of the LCA tool. It has been shown that today there is a lack of stakeholder involvement resulting in LCA studies which only partly fulfil the expectations of the contractors. In this spirit it was recognised, at present, that most of the LCA studies on telecommunication equipment result in bulky and stakeholder unspecific compilations of findings impossible to be used in rapid decision-making. This aspect may explain why LCA so far is not or only partly integrated into decision-making of globally integrated industries, such as in telecommunication industries.

Conclusions. In summary, it can be stated that LCA represents a promising alternative to analyse, to interpret and essentially to adjust the environmental performance of electronic telecommunication products. The review showed that there is a need to focus research efforts in order to arrive at sound improvements of the LCA methodology.

Perspectives. The conclusions from the presented review suggest concentrating in particular on further development of the LCA methodology with respect to efficiency, effectivity and flexibility. This challenge is associated with the need for LCA to be understood as a process rather than a discontinuously applicable tool, attending industrial processes, in essence to contribute to improved environmental performances of products. In this context, particular attention should be paid to proper stakeholder involvement and continuous exchange of concentrated information relevant for the respective stakeholder.

Keywords: End-of-Life; GSM; ISO; life cycle assessment; telecommunication; UMTS